THERMAL VELOCITIES ARISING FROM INJECTION IN 2-PHASE AND SUPERHEATED RESERVOIRS

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ABSTRACT

Production from and injection into geothermal reservoirs gives rise to temperature fronts that move through the porous medium. As many as two temperature fronts are observed in 1-D simulations. The first front is related to the saturation temperature of the production pressure. Its velocity can be calculated from the amount of excess heat in the reservoir, defined as the amount of energy above the interface temperature, $T_i = T_{sat}(P_{wf})$. The second temperature front velocity is the same as for single phase liquid conditions.

INTRODUCTION

Injection of spent geothermal fluids or additional makeup water has long been recognized as necessary to increase energy extraction efficiency. In addition to meeting environmental requirements for condensate disposal, injection serves to maintain reservoir pressure and provides additional working fluid required for energy extraction. Despite the obvious benefits of injection, injection of cool fluid will lead to the cooling of produced fluid, a direct result of improved energy extraction efficiency. The need for fluid injection far outweighs disadvantages; however, care must be taken to design injection strategies such that short-circuiting within the reservoir does not occur.

In two-phase and superheated geothermal reservoirs, some of the injectate boils, thereby improving energy extraction efficiency (comsumption of sensible heat by boiling efficiently removes energy from the rock mass). This leads to increased thermal velocities and a more rapid decline in production temperatures compared to a single phase liquid reservoir. Injection into superheated reservoirs has been studied by various workers. Pruess et al. (1987) developed an analytic solution to mass and energy balance equations, and showed that the rate of boiling at the fluid interface is a function of injection rate, degree of superheat initially present in the reservoir, and various reservoir properties (e.g., permeability, porosity, and thermal properties). Woods and Fitzgerald (1993) extended that work and showed that injection geometry plays an important role as well. They further identified upper and lower bounds on the mass fraction vaporizing that are related to initial and interface pressures and temperatures.

This study was undertaken to evaluate the effect a fixed extraction pressure has on the propagation of temperature velocities in two phase and superheated geothermal systems. The ultimate goal of the study is to use tracer test analysis to predict temperature front velocities that are initiated by cool liquid injection. That goal is not yet realized; however, thermal velocities are derived as ratios of single phase fluid velocities, and are shown to be a function of the degree of superheat available in the reservoir. This superheat can be due to the presence of true reservoir superheat or be induced by production.

ONE-DIMENSIONAL SIMULATION RESULTS

A simple, one-dimensional model was developed to illuminate the controls on thermal velocities. The base case conditions were that of saturated steam at a pressure of 3380 kPa (saturation temperature ~240°C). A non-zero liquid saturation ($S_{wI} = 0.0001$) was used primarily to ensure saturated initial conditions.

At time t=0, 35 °C liquid was injected at a rate of 1.4×10^{-3} kg/s/m-thickness. The other end of the domain was held at a constant production pressure of 2500 kPa. This reduction in pressure induced a boiling front within the reservoir, and led to superheated conditions near the extraction end. The simulation proceeded until extraction temperature was approximately equal to injection temperature (i.e., all usable energy extracted from reservoir).

The temperature history for this case is given in Figure 1. Several interesting observations can be made from this figure. First, there is an abrupt change in the temperature of the produced fluid at approximately 95 days. At this time, the production temperature falls to the saturation temperature for the production pressure. We define this to be the interface temperature, $T_i = T_{sat}(P_{wf})$. Temperature remains constant for an extended period of time while two-phase production occurs, then falls gradually to the injected temperature. Thus, two

temperature waves are observed, with velocities v_{Ti} denoting the velocity of the interfacial temperature, T_i, and v_{TJ} the velocity of the injected temperature, T_J.
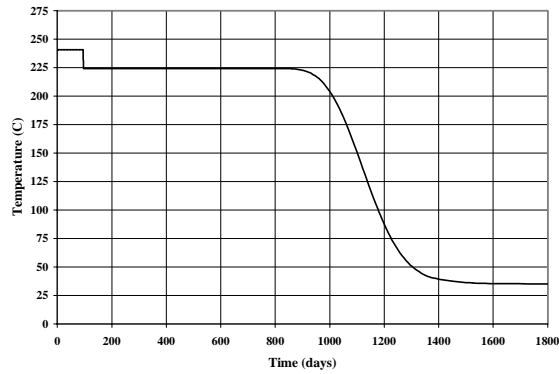

Figure 1.   Temperature history for base case simulation.

Liquid saturation profiles just before breakthrough of the temperature wave show similar behavior (see. Figure 2). There is an abrupt discontinuity in liquid saturation at the leading edge of two–phase conditions, followed by a long tailing of increased liquid saturation. This saturation profile demonstrates the cause of the extended nearly-isothermal production conditions: P_{wf} is fixed, and two-phase conditions exist for a long period of time, thereby forcing constant T_i.
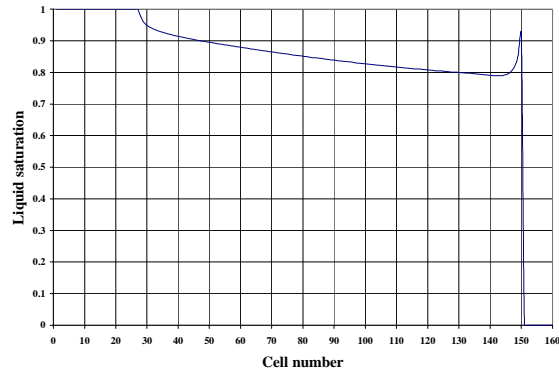

Figure 2. Liquid saturation profile for base case at t=90 days (breakthrough of 2-phase occurs at 95.5 d).

Numerous additional simulations were conducted to evaluate the stability of the two phase production conditions and the liquid saturation profile noted in Figure 2. A brief summary of properties that were varied from the base case and subsequent output of interest is given in Table 1. In all cases, similar responses were observed: a sharp drop in effluent temperature that corresponded to two-phase production, and a sharp liquid saturation front followed by a gradual increase of liquid up to single

phase conditions. Figures 3 and 4 show examples of this observed behavior. Changes in effluent temperature, liquid saturation at the shock front, and changes in the breakthrough time are related to "excess heat," which is described below.

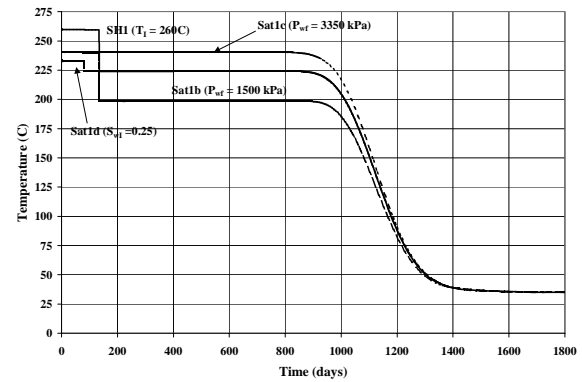| Run #	Change fr. Base Case	t^{BT} for T_i (days)	Liq. Sat at front, S*
Sat1a	Base case	95.5	0.78
Sat1b	Pwf=1500 kPa	134.	0.68
Sat1c	Pwf=3350 kPa	70.1	0.85
Sat1d	S_{wI} = 0.25	79.3	0.82
Sat1f	Pwf=3250 kPa	73.9	0.85
Sat1g	Pwf=1000 kPa	154	0.64
SH1	T_I = 260 C	134.3	0.74
SH2	T_I = 280C	176.	0.72

Figure 3.   Temperature histories for various cases reported in Table 1.

THE CONCEPT OF "EXCESS HEAT"

The temperature change within the reservoir (but seen at the extraction well) is a result of consumption of sensible heat by boiling injectate. The amount of sensible heat available for boiling can be calculated as the difference between rock energy at some initial condition and at the extraction condition (T_{wf}). This initial condition may be identically the initial condition or some "modified initial" (IC') condition, depending on the amount of liquid initially present in the reservoir, as discussed below.

If there exists a liquid saturation, some of that fluid will boil when the pressure is reduced to P_{wf}, thereby consuming energy and reducing energy available for boiling injectate. Defining R as the mass fraction of liquid that boils, we can determine the modified initial temperature, T_I, and saturation, $S_{wI'}$.

$$R = \frac{(1-\varphi)\rho_R C_{pR}(T_I - T_i) + \varphi\rho_{wI}S_{wI}C_{pw}(T_I - T_i)}{\varphi\rho_{wI}S_{wI}\left[C_{pw}(T_I - T_i) + L_{vI}\right]}$$

(1)

Where T_i is defined as the interface temperature, and is identically equal to the saturation temperature at P_{wf}. Three possible cases exist.
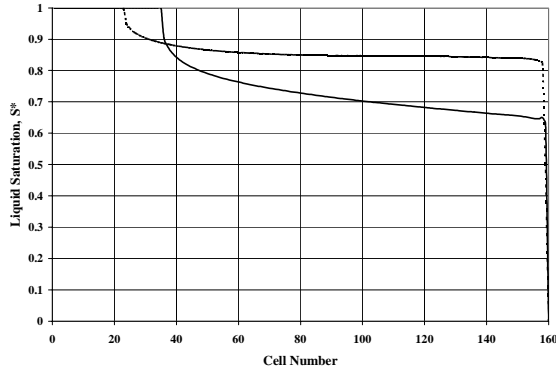

Figure 4. Liquid Saturation extremes for simulations in Table 1 at near-breakthrough times of T_i. S for all cases range from 0.85 to 0.64.*

Case 1. $T_{wf} \geq T_I$, no boiling occurs

In this case, the initial liquid saturation must be unity, and no boiling would occur. The first temperature wave, which arises only from boiling, does not exist. The ratio of fluid velocity to temperature velocity is proportional to the ratio of volumetric heat capacities, as described elsewhere (e.g., Bodvarsson, 1972).

$$v_{T_J} = v_w \frac{\varphi\rho_w C_{pw}}{\varphi\rho_w C_{pw} + (1-\varphi)\rho_R C_{pR}}$$

Case 2. Partial boiling of the initial liquid

In case 2, sufficient liquid originally exists in the reservoir to consume all "excess heat" available (R < 1 in Equation 1). Production temperature falls immediately to T_i and two-phase conditions exist for an extended time. The IC' conditions can be calculated as

$$S_{wI'} = \frac{\rho_{wI}S_{wI}(1-R)}{\rho_{wi}}$$

and

$$T_{I'} = T_i$$

Excess heat, as defined above, is zero in this case, and no boiling of injectate would be expected. The velocity, v_{Ti}, of T_i in this case is infinite; the second temperature velocity is as described above for Case 1.

Case 3. Superheated IC' conditions prevail

In the third case, which is the focus of this study, insufficient liquid is initally present, such that superheated conditions prevail in the neighborhood of the production well. Depending on the amount of liquid initally present, the initial temperature may change to some "modified initial" temperature, $T_{I'}$ ($T_I > T_{I'} > T_i$). $T_{I'}$ can be determined from the amount of liquid that boils (R=1), and the excess heat available to boil injectate can be calculated (neglecting the small amount of energy in the vapor phase, which is largely displaced):

$$T_{I'} = T_I - \frac{\varphi\rho_{WI}S_{wI}L_{vI}}{(1-\varphi)\rho_R C_{pR}}$$

(2)

$$E_{hi} = (1-\varphi)\rho_R C_{pR}(T_{I'} - T_i)$$

(3)

This excess heat is then available to boil injectate which gives rise to an interface temperature wave. The velocity of this wave, v_{Ti}, can be calculated as:

$$v_{Ti} = v_w \frac{\varphi\rho_{wI}L_v}{\varphi\rho_{wI}L_v + (1-\varphi)\rho_R C_{pR}(T_{I'} - T_i)}$$

(4)

We can cast this velocity in a form similar to that used by Shook (2001) for a single phase thermal velocity by defining a retardation factor, D_{Ti}:

$$D_{Ti} = \frac{(1-\varphi)\rho_R C_{pR}(T_{I'} - T_i)}{\varphi\rho_{wI}L_v}$$

$$v_{Ti} = v_w \frac{1}{1 + D_{Ti}}$$

Using the same simulations as given in Table 1, we have verified the accuracy of the predicted temperature velocity, v_{Ti}. A comparison between predicted and observed temperature velocities is given in Figure 5. Excellent agreement is observed for all cases (maximum relative error is 6%), indicating the validity of Equation 4.

SUMMARY AND FUTURE WORK

In situations where production pressures are fixed, injection and production operations create temperature fronts that propagate through porous media. From simple 1-D simulations, it appears that up to two waves are created. The first reduces the production temperature from an initial temperature, $T_{I'}$ to T_i in a shock wave; the second reduces temperature from T_i to the injection temperature, T_J, in a gradual fashion (a spreading wave). Using the

concept of "Excess heat" the velocities of these two temperature waves may be determined (relative to the single phase fluid velocity).
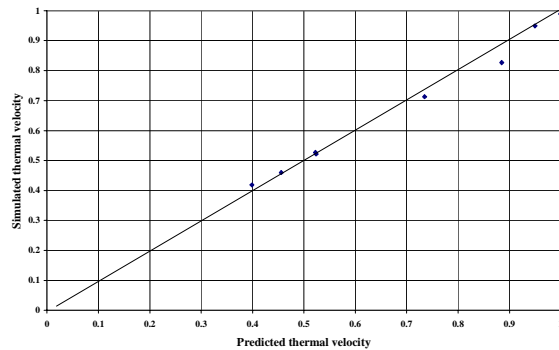

Figure 5. Comparison between predicted and simulated thermal velocities.

Figure 5 clearly shows that Equation 4 predicts temperature velocities accurately. Nevertheless, difficulties in using the method exist. In superheated geothermal systems, single phase fluid velocities are generally not known, and so, while relative velocity is readily calculated, true thermal velocity is still unknown. Additional work is required to estimate the single phase fluid velocity from other sources (e.g., tracer tests).

ACKNOWLEDGMENTS

NOMENCLATURE

C_{pr}	rock specific heat (J/g^{o}C)
C_{pw}	liquid specific heat (J/g^{o}C)
E_h	Excess heat as defined by Eqn. 3 (J)
L_v	Latent heat (J/g)
R	Mass fraction of liquid that boils
T	temperature (^{o}C)
t^{BT}	breakthrough time for either fluid (w) or temperature (T)
T_I	initial temperature (^{o}C)
$T_{I'}$	modified initial temperature fr. Eqn. 2 (^{o}C)
Ti	interface temperature $=T_{sat}(P_{wf})$
T_J	injected temperature (^{o}C)
v_{Ti}	velocity of interfacial thermal front (L/t)
v_{TJ}	velocity of injected temperature front (L/t)
v_w	interstitial velocity of fluid (L/t)
φ	porosity (fr)
μ	viscosity (mPa-s)
ρ_r	rock density (kg/m^3)
ρ_w	liquid density (kg/m^3)

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